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Lewis Rearch Center
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ABSTRACT

An experimental study of changes in the electrical characteristics and cell surface temperatures of CdS solar cells was performed. The experiments showed that cells maintained at 25° C and open circuit load degraded in shunt resistance and electrical output when exposed to air-mass-one illumination (100 mw/cm^2) for periods up to hundreds of hours. The cells also developed hot spots. Cells subjected to dark forward biases, with current flow of 0.5 to 1.0 ampere, degraded in a similar manner and developed hot spots in only a few minutes time. The nature of the degradation in both cases suggests the formation of localized shorting paths across the barrier. Recovery of cell performance was produced 1) by reverse biasing the cells in the dark, 2) by excision of hot spot regions of the cell, or 3) by storage of the cells in the dark.

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SUMMARY

An experimental study of changes in the electrical characteristics and cell surface temperatures of degraded CdS solar cells was performed. The CdS solar cells were degraded in the dark by applying a forward bias, and in the light by leaving the cells at open circuit. Changes in cell surface temperature were monitored during and after degradation by means of an infrared viewing device and by temperature sensitive liquid crystals.

The experiments have shown that cells maintained at 25° C and open circuit load degrade in shunt resistance and develop hot spots when exposed to air-mass-one illumination (100 mw/cm^2) for periods up to hundreds of hours. The shunt resistances of the four cells tested were reduced by 50 to 95 percent after 260 hours of illumination. Reductions of 20 to 50 percent in maximum power and 5 to 10 percent in open circuit voltage were also observed. The short circuit current was least affected by the test, showing reductions of less than 5 percent.

Accelerated degradation of cells was produced by subjecting the cells to dark forward biases with a current flow of 0.5 to 1.0 ampere for several minutes. Cells degraded in this manner showed reductions in

shunt resistance, maximum power, and open circuit voltage, similar to cells degraded by constant illumination. The degradation under forward bias was also associated with the appearance of hot spots on the cell surface.

Cell recovery was produced 1) by applying dark reverse bias, 2) by excision of hot spot regions of the cell, or 3) by storage of the cells in the dark. As the cell output recovered, the hot spots disappeared and the shunt resistance increased.

INTRODUCTION

Thin-film cadmium sulfide (CdS) solar cells are currently being tested in simulated space environments to determine the performance over long periods of time in space (ref. 1). From the inception of the testing program, the CdS cells have been observed to degrade in performance during these long term cycling tests. The reasons for the degradation have not been determined. A determination of the causes of degradation has been hampered by the length of the tests and the inaccessibility of the cells during the tests.

Tests under other conditions, not necessarily pertinent to the space applications, are being made. These tests are made to identify weaknesses in the cells, and ultimately to determine whether they are related to the degradation in the simulated space tests. Cells have been found to degrade rapidly under constant illumination at open circuit voltage in air. Greater degradation was observed when cells were loaded at open circuit voltage than when loaded at the more normal condition of maximum power (ref. 2). Also, hot spots have been observed on cells with an infrared viewing device when unilluminated cells were biased in the forward (copper sulfide positive) and reverse directions (ref. 3). It was of interest to determine whether the hot spots were related to changes in cell electrical characteristics.

Therefore, an experimental study was initiated to examine the temperature patterns on the cell surface and the electrical performance under various testing conditions. The cells were tested in air under constant illumination at open circuit voltage and under no illumination at several values of bias voltage. In this report are described the changes in electrical performance and observed temperature patterns.

SYMBOLS

AM1	Air Mass One, the spectral distribution and intensity of sunlight on earth at sea level with the sun directly overhead and passing through a standard atmosphere.
AMO	Air Mass Zero, the spectral distribution and intensity of sunlight in near-earth space without atmospheric attenuation.
I_{SC}	Short circuit current, ampere.
I-V	Current-voltage.
P_M	Maximum power, watt.
R_{SH}	Shunt resistance, ohm.

APPARATUS

Solar Cell Test Apparatus -- This apparatus consists of a water filtered tungsten light source, a temperature-controlled block with vacuum openings to hold cells in place, and an electronic load which varies the load across the cell from V_{OC} to I_{SC}. An X-Y plotter was used to record the I-V curve. The tungsten source is adjusted during I-V measurements, by means of a CdS, airplane flown, standard (ref. 4), to irradiate the control block surface at a one solar constant (136 mw/cm^2) intensity level. The intensity is reproducible to ±0.3 percent of one solar constant and the estimated light uniformity over the test plane is ±2 percent. Based upon an analysis-of-variance study (ref. 2), the standard deviations of the V_{OC}, I_{SC}, and P_M are ±1.3 mv, ±2.1 ma, and ±2.8 mw, respectively.

Transistor Curve Tracer -- This instrument was used to bias the cells. The applied voltage across the cell is swept from zero to a preselected peak voltage at a frequency of 120 hertz. The instrument contains a cathode ray tube which displays the I-V characteristic while the cell is under bias.

Infrared Viewing Device -- The infrared device used to view temperature changes on the cell surface is shown in figure 1. The field of view of the camera is 5° by 5° and the display unit frame size is 42 mm by 54 mm. Spatial resolution of the display is 0.5 mm and the thermal resolution is about 0.2° C (ref. 5). A photograph of the display, called a thermogram, is obtained using a photographic camera for a permanent record of the image.

Temperature Sensitive Liquid Crystals -- Changes in the temperature distribution of cell surfaces were also detected with cholesteric liquid crystals sensitive in the 40° to 42° C temperature range. The commercially produced crystals were applied in the form of a thin film using an air brush.

A description of the properties and uses of the liquid crystals is given in reference 6.

Experimental Procedure

Unilluminated Tests

Unilluminated forward and reverse bias tests of the CdS solar cells were made on approximately twelve cells manufactured in April and May of 1968 (ref. 7). The I-V characteristics were displayed on the curve tracer and were photographed for record. During biasing, the temperature patterns of the cells were monitored with the infrared viewing device as well as with liquid crystals. By varying the bias and using a microscope, hot spots on the cells were resolved to about 50 μm.

Illuminated Tests

The CdS cells tested under constant illumination were randomly selected from cells produced in September, 1968. Three of the four cells tested had not been tested previously except for the measurement of the I-V characteristic at the time of fabrication. Since fabrication, the cells had been kept in dry, dark storage. The fourth cell had been tested, under constant illumination while open circuited, for about six days in an earlier experiment.

Prior to the constant illumination tests reported here, the following measurements were made on the four cells. The dark I-V characteristic was measured between +200 ma and -25 ma. The temperature distribution of the cells was checked with the temperature viewing device during the dark measurement and while the cells were illuminated with simulated sunlight of AMO intensity. The illuminated temperature check was made with the cells held momentarily at I_{SC} and V_{OC}. The cells then were exposed to constant illumination of approximately AM1 intensity for 260 hours. During the light tests, the cells were in air at ambient pressure and humidity (55 to 75 percent) and were held at 25° C ± 1° C. They were held at V_{OC} except during the periodic electrical measurements when the load was varied momentarily from V_{OC} to I_{SC} to record the I-V characteristic. The light intensity was raised to the AMO value whenever an I-V characteristic was measured. Values for I_{SC}, V_{OC}, and P_M were obtained directly from the I-V traces. Values for the R_{SH} were approximated from the slope of the I-V trace at I_{SC}. Thermograms of each cell were also made periodically.

After the constant illumination period, the light source was shut off and the cells covered with black paper. Otherwise, cell conditions were the same as during the light period. The cells were kept in the dark for 163 hours with only occasional interruptions for checking the I-V characteristic which required illuminating the cells for a few minutes. The cells were then subjected to an additional 334 hours of constant illumination during which the procedures and conditions were the same as the initial light period. At the completion of the second light period, dark I-V measurements were made for comparison with the pre-test measurements. The cells were also sprayed with liquid crystals to define more precisely the temperature distribution on the cell surface.

RESULTS AND DISCUSSION

Unilluminated Tests

The dark I-V characteristics of CdS solar cells were found to change when a forward current of 0.5 ampere to 1.0 ampere was applied to unilluminated cells. The voltage across the cells was 1.0 volt to 1.75 volts. Figure 2 shows the initial and degraded I-V curves of a typical cell.

Within minutes after the bias was applied, the I-V characteristic began a gradual transition toward the ohmic state. Primarily, the dark shunt resistance decreased, such that at a fixed voltage, the current increased. This manner of change suggests that a bias-induced shorting path was forming which was shunting the barrier layer. During this period, at least one circular or elliptical hot spot appeared on the cell surface. These hot spots always coincided with a cell grid wire. This gradual transition was followed by an intermediate stage in the degradation process in which the I-V curve randomly fluctuated between an ohmic and a rectifying characteristic. Finally, the cell formed a stable ohmic curve and a single hot spot. The total time for the cell to degrade was less than 15 seconds, but this varied from cell to cell with some cells taking several minutes before degradation began. Thermograms taken before and after degradation show the resulting hot spot (fig. 3). The hot spots were usually located near the cell edges. Increasing the forward bias to 3 amperes did not effect the ohmic I-V curve. The increase however did increase the temperature and diameter of the hot spot. Hot spot temperatures in excess of 100° C were detected for some cells passing a current of about one ampere.

When a reverse bias of about -1.0 ampere, -0.5 volt was applied to the degraded cell, an abrupt recovery of rectification occurred within a few seconds (fig. 2). The I-V curve was improved, compared to the initial trace, in both the forward and reverse directions. The rapid recovery, similar to a switching phenomenon, was accompanied by the disappearance of the hot spot. Just prior to recovery, the hot spot momentarily increased in temperature and then disappeared. Usually, a small translucent bubble appeared under the cell cover plastic where the hot spot had been located. The degradation-recovery process was repeatable and was always accompanied by the formation of a hot spot at a new location, usually in the vicinity of the previous one.

The photovoltaic I-V characteristic is shown in figure 4 for a typical cell before and after unilluminated, forward bias degradation. The characteristic after reverse bias recovery is also shown. The cell in the degraded state clearly shows the effects of a low shunt resistance. There is a loss in maximum power and open circuit voltage. The thermogram (fig. 5) of the open-circuited cell exposed to about 70 mw/cm^2 illumination shows the hot spot in the same location as it appeared under unilluminated forward bias. Increasing the intensity of illumination also caused an increase in hot spot temperature and diameter. These effects are consistent with the idea that unilluminated forward bias degradation is a result of shorting path formation.

As shown in figure 4, successive retraces (curves near b) of a degraded cell induces a slight recovery in the photovoltaic characteristic. These retraces, however, produced little or no improvement in the dark I-V curve. This suggests that the photovoltaic I-V trace may be a more sensitive indicator of recovery processes. The hot spot appeared unaffected by the slight recovery.

The dark and photovoltaic characteristics could be fully restored by also cutting out the hot spot area. Curve d in figure 4 shows the restoration of the photovoltaic I-V characteristic by this method. The loss in I_{SC} is accounted for by the loss in cell area due to excision of the hot spot. The same cell was degraded several more times, always accompanied by the formation of hot spots. Excision of the hot spot always recovered the dark and photovoltaic characteristics. In general, the ability to restore a degraded cell by excision of the hot spot indicates that the degradation process occurs only in a local cell region, usually near the cell edge.

Illuminated Tests

The effect of constant illumination, open-circuit conditions on the photovoltaic I-V curve of CdS solar cells is shown in figure 6. Curve a shows the initial cell output and curves b, c and d show the output after 4, 9 and 11 days, respectively. This type of change in the I-V curve is characteristic of a decrease in the shunt resistance of the cell. Decreases in R_{SH} of 50 percent to 95 percent were noted for the four cells tested. Reductions in P_M of 20 to 50 percent and V_{OC} of 5 to 10 percent also occurred. During the degradation of the I-V characteristic, hot spots formed on the cells. The hot spots disappeared during the measurement of the I-V curve. The disappearance of the spots occurred between the knee of the curve and short circuit current. When the cells were returned to V_{OC}, the hot spots reappeared.

These changes (i.e., the decrease in R_{SH} and the appearance of hot spots as a result of the open circuit, illuminated test) are similar to the changes observed in the unilluminated forward bias tests. The loss of shunt resistance in both cases is probably due to the formation of localized shorting paths across the barrier. When the shorting paths are present and the cell is near open circuit, much of the current from the cell passes through the shorts, producing hot spots. As the load resistance is decreased from infinity to zero in measuring the I-V characteristic, the resistance of the load at some point becomes less than the resistance of the short. Then most of the cell current passes through the load and the hot spot disappears.

The effect of dark storage on a cell degraded by the illuminated, open-circuit test is shown in figure 7. Curve a shows the cell output at the end of the constant illumination test. Curves b and c show the output after 3 and 6 days respectively of dark storage. Curve d shows the initial output prior to degradation. As mentioned under the unilluminated, forward bias tests, the taking of an I-V trace produces in itself some recovery in the degraded cells (fig. 7b). Therefore, part of the recovery during the dark storage can be attributed to the I-V measurement used to monitor the cell. The I_{SC}, V_{OC} and P_M, of three of the four cells tested, were restored to within 95 percent of the initial values. The remaining cell, which was the cell that had been tested in an earlier experiment, only recovered to 82 percent of the initial P_M. The cells also showed some recovery in R_{SH}, due to dark storage. The cell represented in figures 6 and 7 had an initial R_{SH} of

17 ohms which decreased to 1 ohm during the test. After dark storage, the R_{SH} was 12 ohms. This indicates that the shorting paths which resulted from the illuminated test were only partially removed due to the dark storage. However, the increase in R_{SH} from 1 ohm to 12 ohms was sufficient to make the hot spots disappear.

Since the R_{SH} was not recovered entirely by dark storage, one might expect the cell to decrease in output at a faster rate when subjected to a second illuminated, open-circuit test. Figure 8 shows the changes in the electrical performance as a function of time for one of the cells tested. During the first illuminated period, it took 180 hours for the P_M to decrease by 25 percent. After recovering in the dark to 95 percent of the initial value, it took only 68 hours for the P_M to decrease the same amount. Although the rate at which the cells degraded varied from cell to cell, all the cells degraded in less time during the second illuminated, open-circuit test than the first. The hot spots which appeared during the first test also reappeared in the same location during the second test. Dark storage of cells degraded under illuminated open circuit tests therefore provides only temporary recovery of the electrical performance and indications are that upon continued testing, the cells will be easier to degrade.

In addition to the degradation of the photovoltaic I-V characteristic discussed above, changes in the dark I-V characteristic were also observed. Shown in figure 9 are the I-V plots of one of the cells tested. Originally all of the cells had a "normal" dark I-V trace such as curve a.

After the constant illumination tests, two of the four cells tested had ohmic dark I-V traces, such as curve b. A third cell had become less rectifying. The remaining cell was not measured, since it was damaged during removal from the test fixture.

SUMMARY OF RESULTS

1. Exposure of CdS solar cells to a forward bias of 0.5 to 1.0 ampere, while unilluminated, resulted in the following changes:
   a. The dark I-V characteristic became ohmic and hot spots appeared on the cell surface usually in less than a minute.
   b. The photovoltaic I-V characteristic showed reductions in shunt resistance, maximum power, and open-circuit voltage.
   c. Cells degraded by the unilluminated forward bias conditions were recovered by reverse biasing the cells with 1.0 ampere, 0.5 volt for a few minutes or by cutting out the deteriorated region indicated by the hot spot.
2. Exposure of CdS cells for several hundred hours to air-mass-one, simulated sunlight while in air at 25° C and open-circuited resulted in the following changes:
   a. The shunt resistances of the cells decreased by 50 to 95 percent.
   b. The electrical output of the cells, measured under AMO light intensity, was reduced by 20 to 50 percent in maximum power, 5 to 10 percent in open-circuit voltage, and less than 5 percent in short-circuit current.
   c. Small area hot spots appeared on the cells.

d. The dark I-V characteristic became less rectifying and in some cases became ohmic.

e. The losses in maximum power and open-circuit voltage were recovered in three of the four cells tested by keeping the cells in the dark for about seven days. The shunt resistance was only partially recovered by dark storage. As the cell output recovered, the hot spots disappeared. Retesting the cells under constant illumination while open circuited caused the hot spots to reappear and the output to degrade in less time than was required initially.

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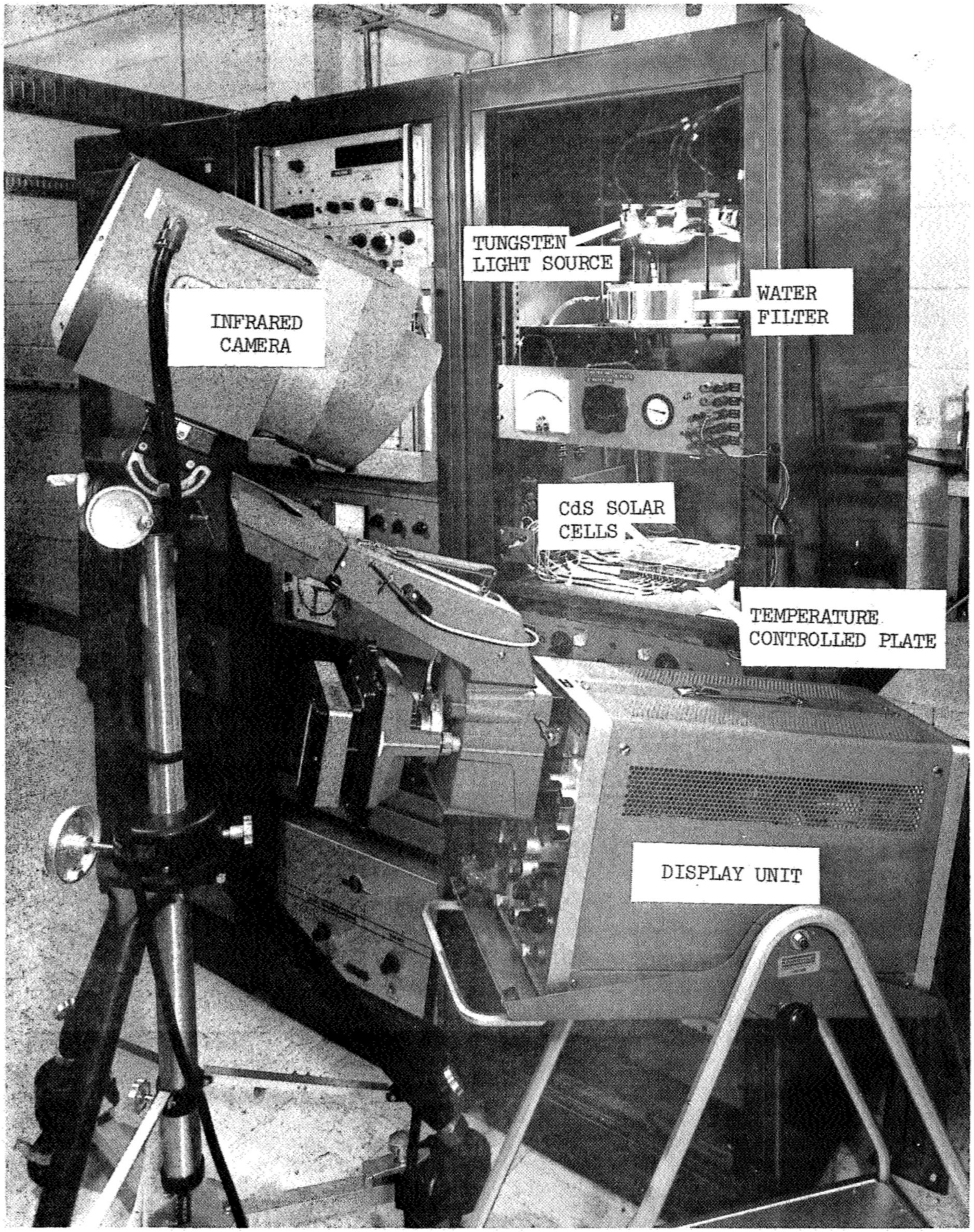


Figure 1 - Solar Cell Test Apparatus and Infrared Viewing Device

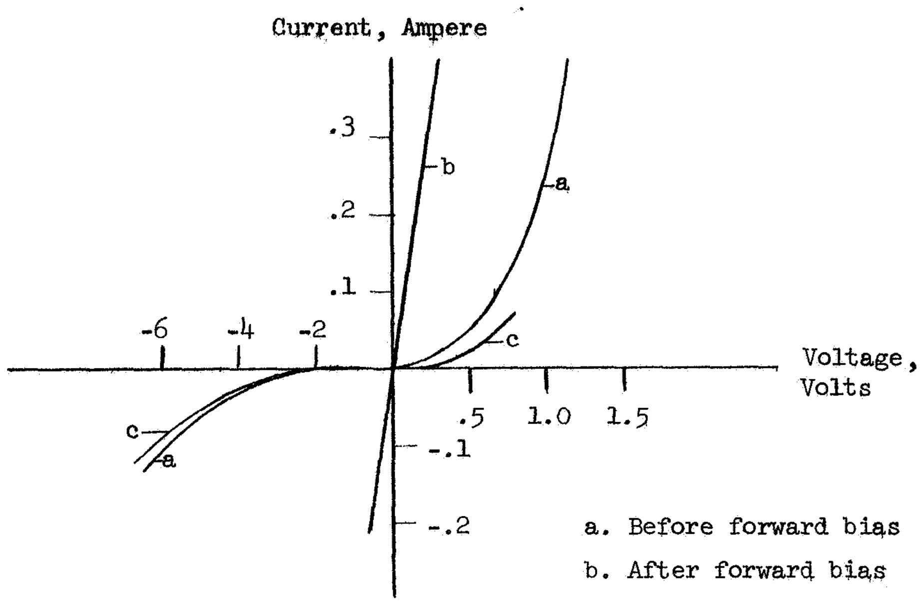
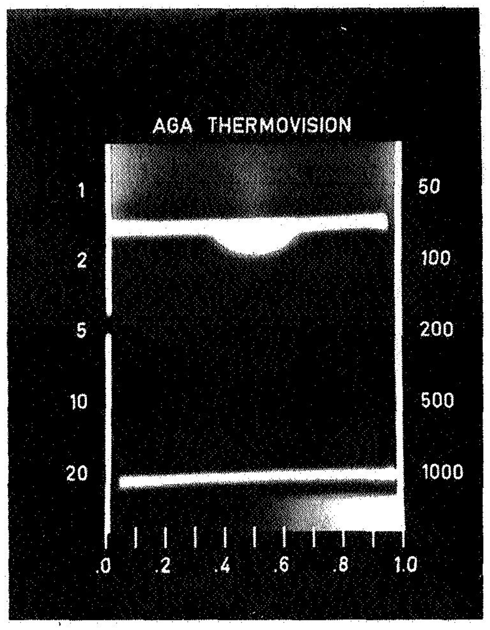
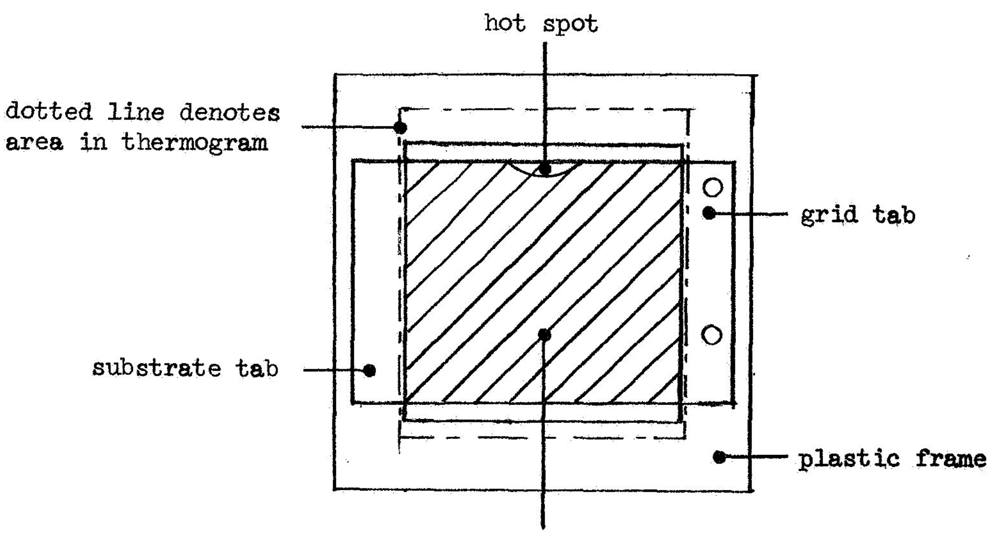


Figure 2 - Dark I-V Characteristics of CdS Solar Cell

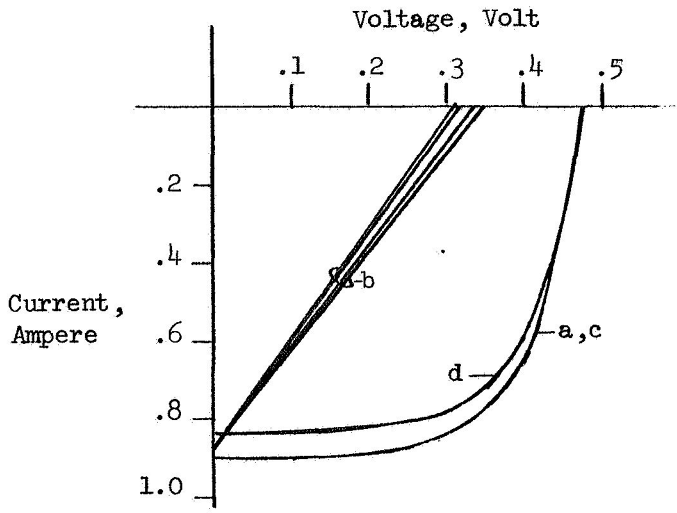


a - Thermogram



b - Schematic showing area in thermogram

Figure 3 - Hot Spot Appearing on Cell Degraded by Forward Bias



a - Before forward bias

b - After forward bias

c - After reverse bias

d - After excision of hot spot

Figure 4 - Photovoltaic I-V Characteristic of CdS Solar Cell

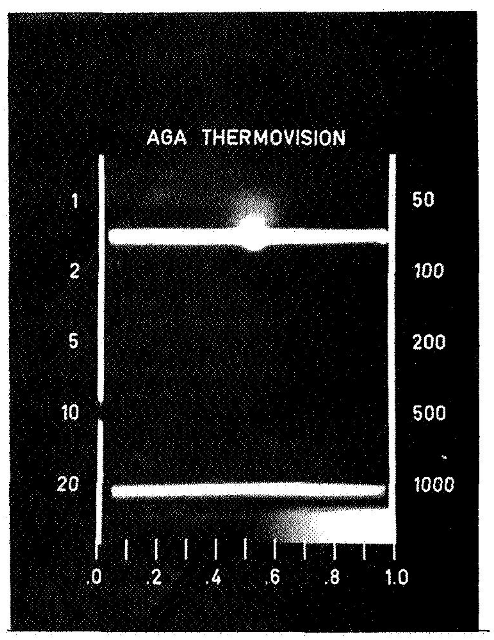
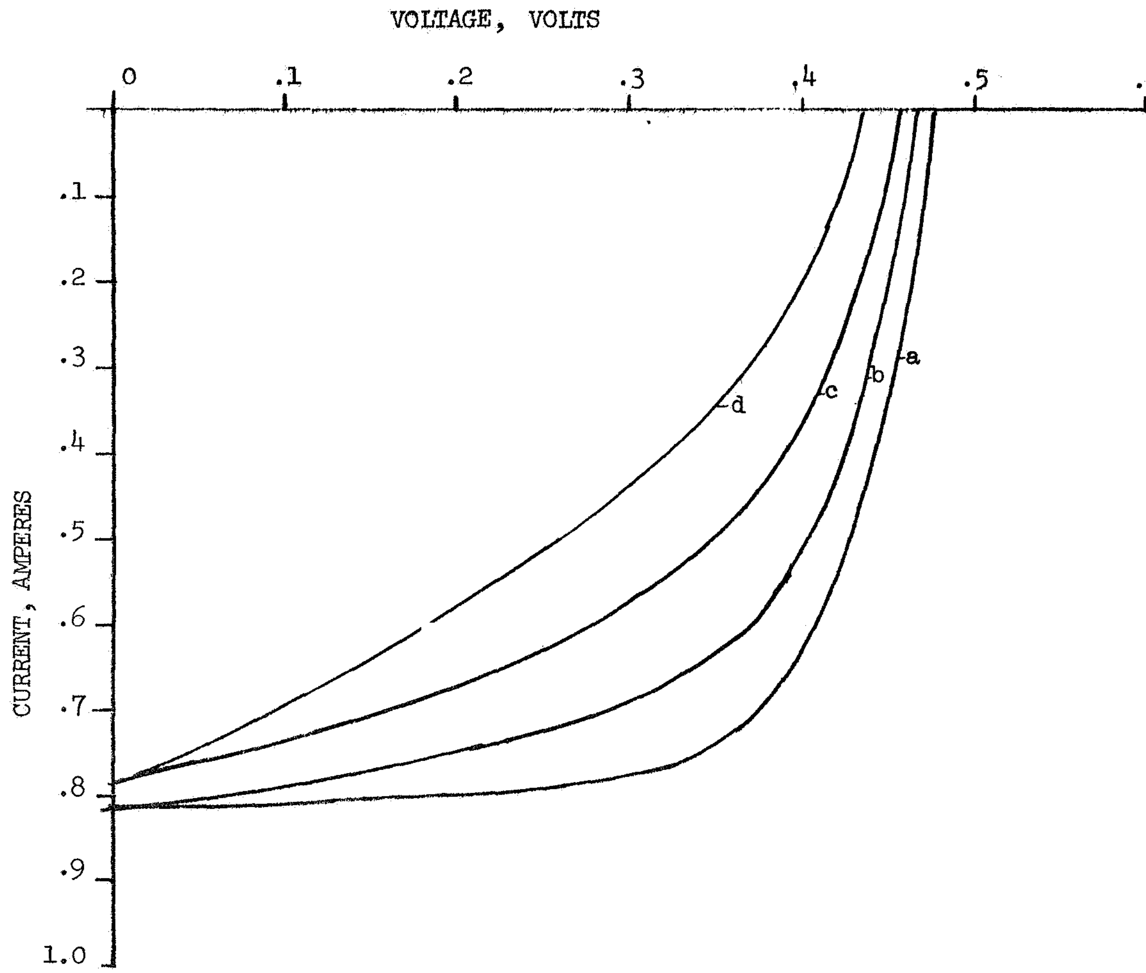
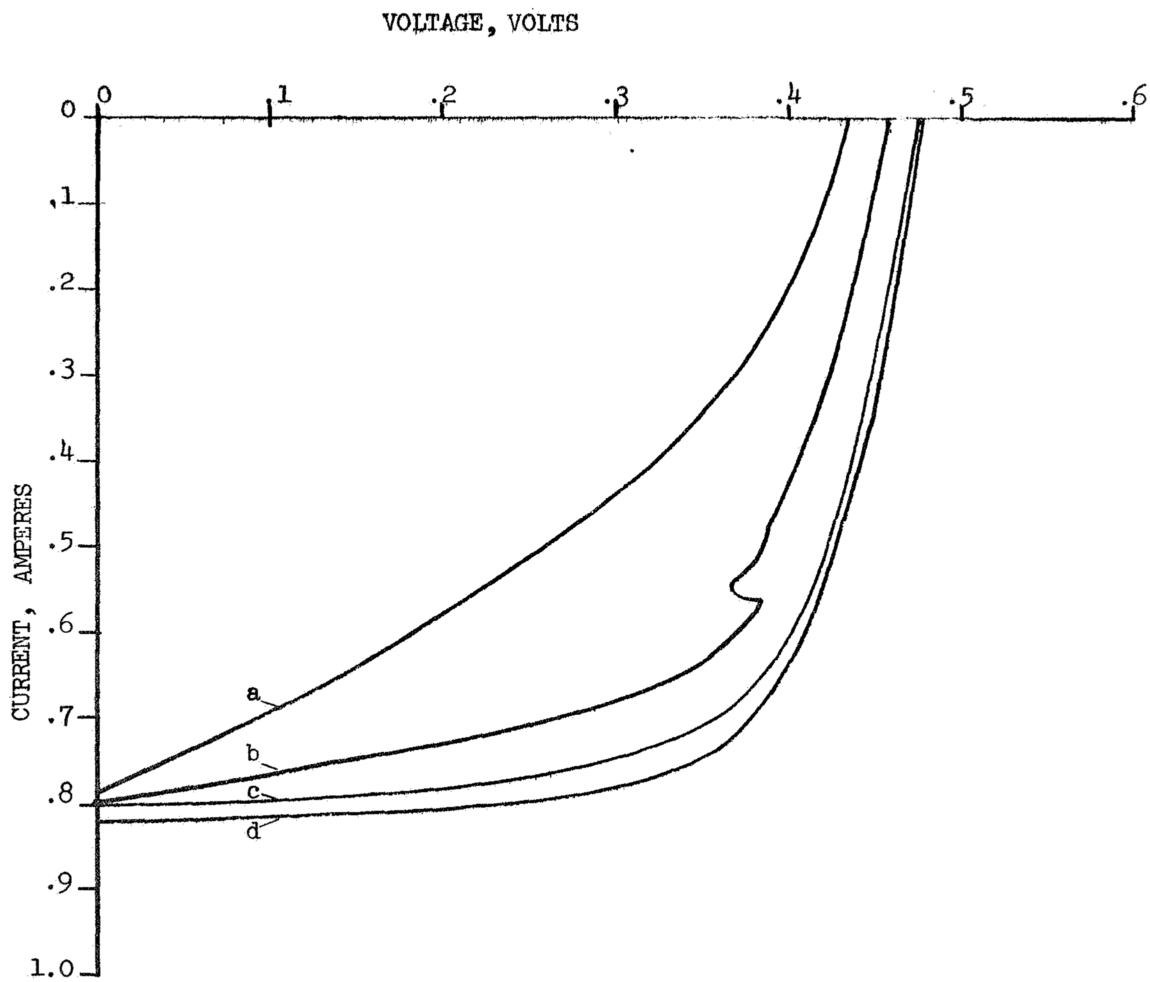


Figure 5 - Hot Spot Appearing on Cell Illuminated at 70 mw/cm^2



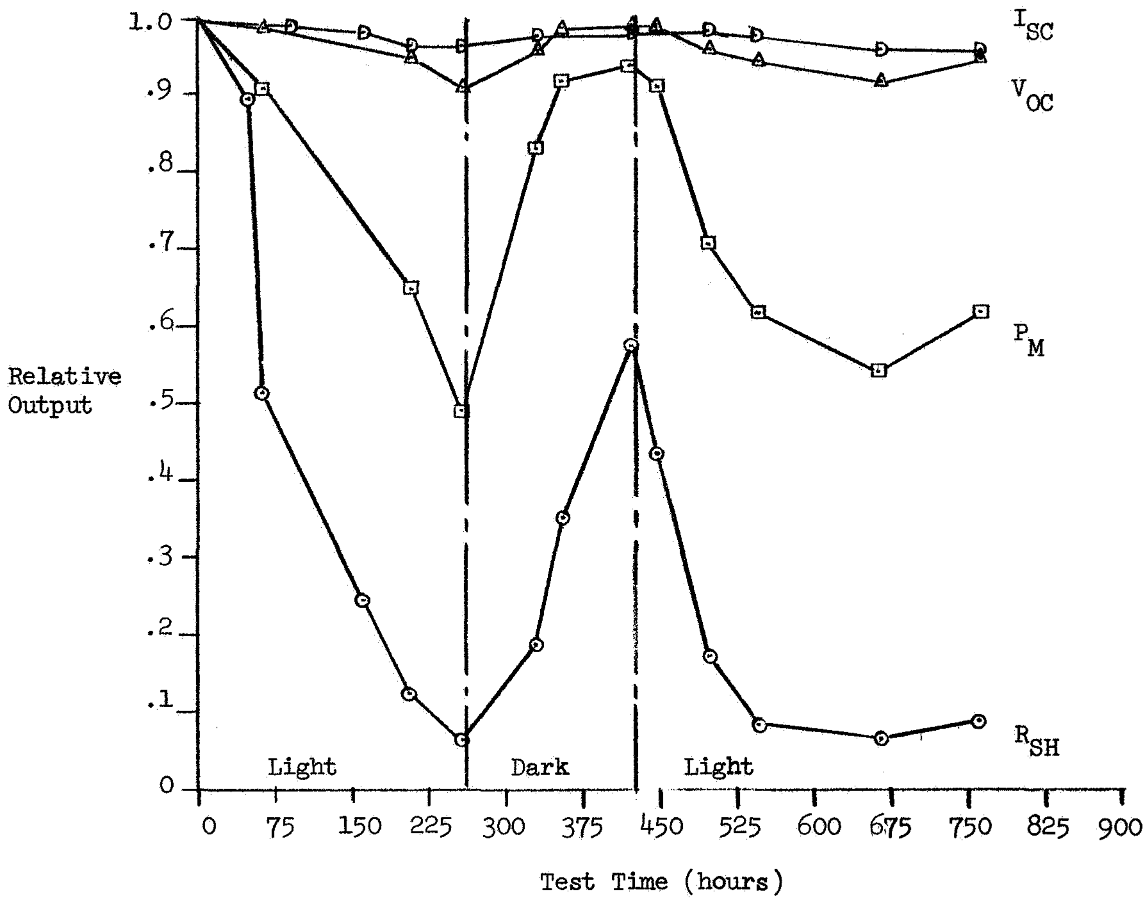
Date	Curve	OCV	SCC	P_{MAX}	R_{SH}	Remarks
10/7/68	a	.477	.816	.266	17	initial I-V trace
10/11/68	b	.467	.810	.220	4	after 4 days on test
10/16/68	c	.454	.787	.173	2	after 9 days on test
10/18/68	d	.435	.789	.131	1	after 11 days on test

Figure 6 - Degradation of the I-V Characteristic During Constant Illumination Tests

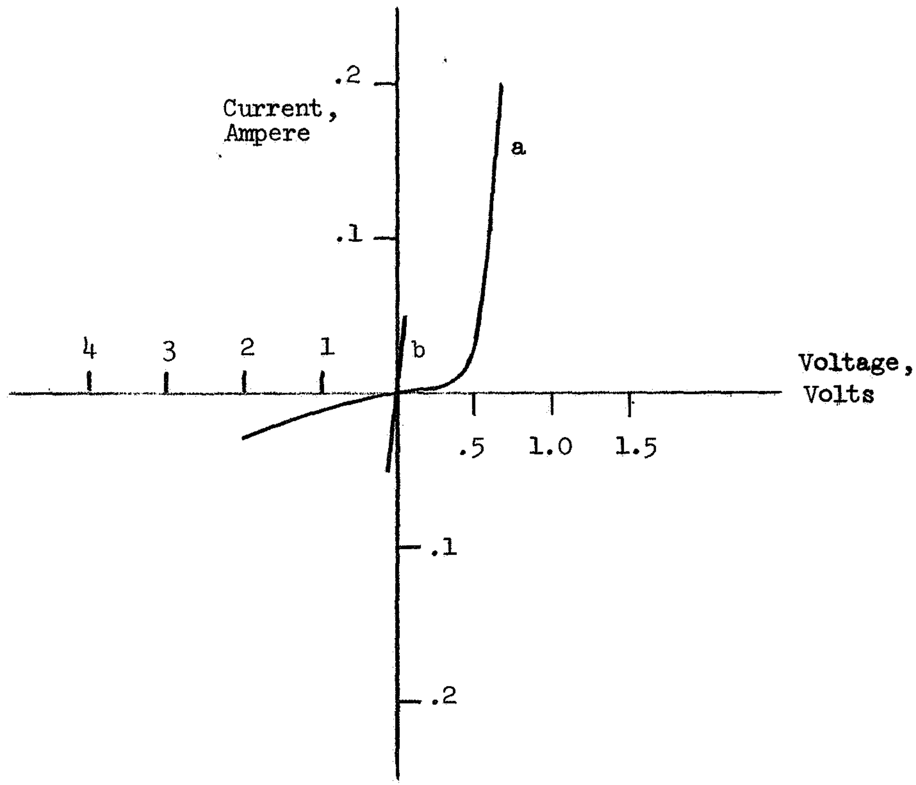


Date	Curve	OCV	SCC	P_{MAX}	R_{SH}	Remarks
10/18/68	a	.435	.789	.131	1	after 11 days on test
10/21/68	b	.457	.799	.222	3	after 3 days dark storage
10/24/68	c	.472	.803	.256	12	after 6 days dark storage
10/7/68	d	.477	.816	.266	17	initial trace, before degradation

Figure 7 - Recovery of the I-V Characteristic During Dark Storage



<u>Figure 8</u> - Relative Output vs Time for CdS Solar Cell Exposed to Constant Illumination and Dark Storage While at Open-Circuit



a - Before constant illumination test

b - After constant illumination test

Figure 9 - Dark I-V Characteristics for CdS Solar Cell Before and After Constant Illumination, Open Circuit Load Test